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Aspherical structural heterogeneity within the uppermost inner core: Insights into the hemispherical boundaries and core formation

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ABSTRACT

Lateral heterogeneities at the top of the inner core are investigated using earthquakes that occurred in Indonesia and southeast Asia and were recorded in the southeastern Caribbean. Using seismic observations of attenuation and seismic velocity, we were able to constrain the characteristics of the boundary between the inner and outer core to further investigate the dynamics and evolution of the Earth's core. Our seismic observations from core phases confirm that the outermost inner core is asymmetrically heterogeneous and we are able to further constrain the morphology and physical properties of this layer. Comparison of data from earthquakes with ray paths traversing from east to the west versus those with ray paths from west to east allow us to map the aspherical heterogeneity of the boundary layer and specifically image the boundary between the proposed quasi-eastern and western hemispheres of the inner core. The variation of differential travel times between PKP_{df} and PKP_{bc}, attenuation in terms of Q factor, and latitudinal changes for both of these observations, can be attributed to localized heterogeneity at the quasi-hemispherical boundaries of the inner core. We constrain the change in the thickness of outermost core boundary layer from 100 to 250 km within a distance of a few 10s of kilometers at $45°E \pm 2°$, for the western boundary, with an overall P-wave velocity decrease in the western hemisphere of 0.5% and increase of 0.5% in the eastern hemisphere. We constrain the eastern boundary at latitudes greater than 45°N to $173°E \pm 4°$ with an overall P-wave velocity decrease in the western hemisphere of 1.0% in the uppermost 200 km of the inner core. The eastern boundary at equatorial latitudes is constrained to a region <170°E with a western hemisphere with a 0.5% drop in P-wave velocity in the uppermost 250 km.

1. Introduction

Evidence of aspherical structure of the inner core using body wave data began with the investigation of travel times of PKP_{df} (PKIKP) (Poupinet et al., 1983). Much of our knowledge of the inner core is based on the observation of this phase, PKP_{df}, which travels through the solid inner core, and the differential travel times between it and PKP_{bc}, a P wave which travels through the deep portion of the liquid outer core (Fig. 1A). Since these two compressional waves have similar ray paths in the mantle and much of the outer core, the differences in travel times and amplitudes between PKP_{bc} and PKP_{df} can be attributed to the vicinity of the inner core boundary. However, the use of these phases have been challenged for accurately interpreting structure in the inner core (Ishii et al., 2002; Romanowicz et al., 2002). As seismic data sets have dramatically improved due to a more extensive distribution of instruments across the Earth over the last 25 years, there has been advancement in the understanding of the complex structure of the inner core.

From analysis of these enhanced data it has been found that the inner core is not simply just a solid, but has distinct structure and heterogeneity, which can be described in terms of attenuation (Q, quality factor), anisotropy, and seismic velocity. Q, which is a dimensionless quantity, is inversely related to strength of the attenuation, so regions with a high Q are less attenuating and those with a low Q are more attenuating. Unlike the outer core, which has a Q-value that is almost infinite (Dziewonski and Anderson, 1981), the inner core Q-value has been constrained to values less than 450 (Bhattacharyya et al., 1993). The dramatic change in Q occurs at the inner core boundary and appears to happen within the outermost inner core (Song, 1997). Furthermore, it has been suggested that the inner core is separated into two quasi-hemispheres, with boundaries at ~40°E and ~180°W (Tanaka and Hamaguchi, 1997; Niu and Wen, 2001; Garcia, 2002; Wen and Niu, 2002; Cao and Romanowicz, 2004; Stroujkova and Cormier, 2004; Garcia et al., 2006), and these differences are best observed from seismic phases that sample the outermost inner core.

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Here we further investigate the aspherical heterogeneity of the inner core structure by observing differences in the travel time residuals and quality factor (Q) averages for earthquakes sampling the western hemisphere boundary of the inner core from events occurring in Indonesia recorded at a temporary array in the southeast Caribbean in comparison to earthquakes occurring at the Sunda and Banda arcs which travel in the opposite direction and sample the boundary of the opposite inner core hemisphere. This dataset provides us with a description and understanding of the nature of the boundaries of the inner core hemispheres, and also provides support for the idea that the inner core solidifies from the outer core (Jacobs, 1953), which could be explained by the existence of a mushy zone at the top of the inner core. It has been suggested that as the inner core formed by freezing iron as the liquid outer core gradually cooled, some of the lighter elements in the outer core and may have become concentrated in a mushy or slurry layer at the top of the inner core (Birch, 1964; Gubbins, 1977; Gubbins et al., 2003; Loper, 1978). Using seismic observations of core phases, we are able to constrain the characteristic morphology and properties of the outermost inner core where this layer exists, and from these data learn more about the dynamics and evolution of the Earth.

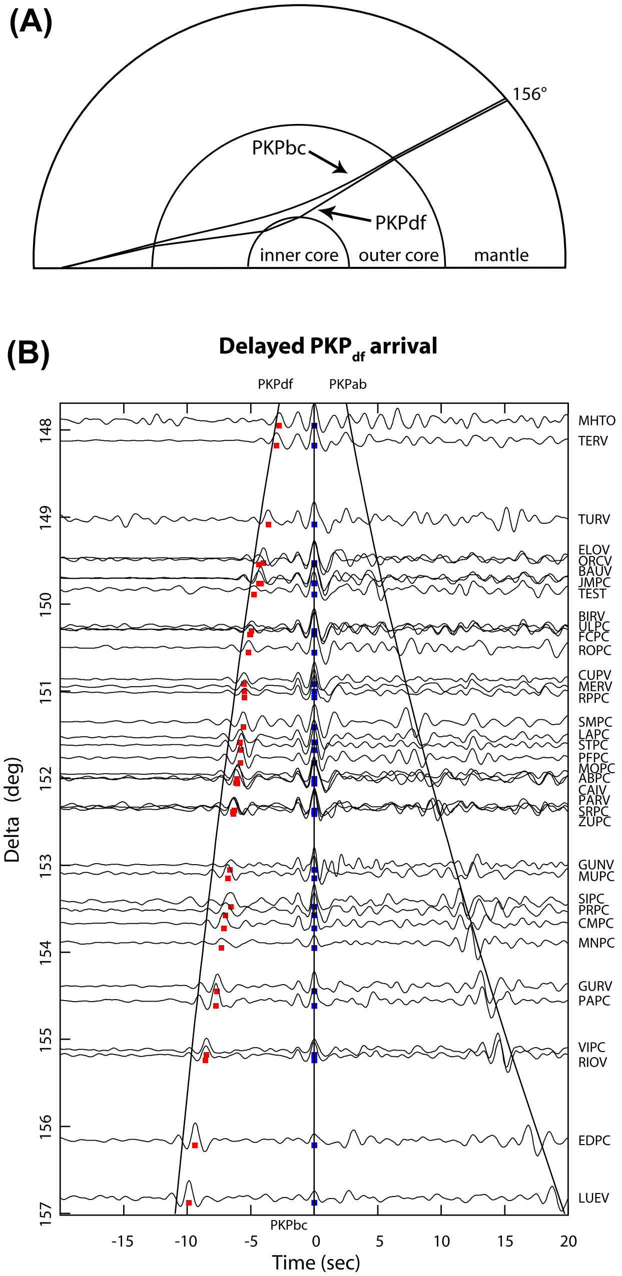

Fig. 1. (A) Ray paths of PKP phases PKP$_{df}$ and PKP$_{bc}$. These two core phases have nearly identical paths through the mantle. (B) Example of a record section for a M_w 5.8 earthquake on 10 April 2002 recorded at the southeastern Caribbean stations. The vertical component seismograms are aligned on PKP$_{bc}$ with station names shown on the right. The red squares are our picks of the PKP$_{df}$ arrival and the blue squares indicate the picked PKP$_{bc}$ arrival. The lines represent the estimated arrival times of the different phases according to PREM (Dziewonski and Anderson, 1981). The horizontal axis (time) is normalized to PKP$_{bc}$. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this article.)

Table 1
Earthquakes used in inner core boundary study.

Event ID	Latitude	Longitude	Depth (km)	Magnitude (Mw)
20040107_1845	20.053	122.185	42	5.6
20040410_0735	8.043	137.215	40	5.8
20040701_1928	−5.91	148.662	56	5.6
20040729_0144	12.455	94.997	22	5.9
20040915_1910	14.22	120.411	115	6.0
20041008_1436	13.925	120.534	105	6.5
20041029_1928	15.643	119.11	21	5.5
20041105_0518	−4.361	143.925	125	6.0
20041128_0736	−3.638	135.445	23	6.2
20041210_0942	10.874	141.781	32	5.5
20041211_0155	−4.613	149.779	541	5.5
20041226_0222	8.868	92.467	15	5.7
20041226_0308	13.745	93.009	30	5.9
20041226_0324	4.473	94.068	26	5.8
20041226_1019	13.462	92.738	26	6.3
20041227_0032	5.476	94.467	33	5.8
20041227_0049	12.982	92.395	23	5.8
20041227_0939	5.348	94.65	35	6.1
20041227_1446	12.35	92.469	19	5.6
20041227_1913	11.586	92.499	25	5.5
20041229_0150	9.109	93.756	8	6.1
20041229_1850	5.531	94.277	47	5.7
20041229_2112	5.23	94.625	29	5.6
20041230_1758	12.237	92.515	30	5.7
20041231_1204	6.204	92.913	11	6.0
20050101_0403	5.465	94.398	36	5.7
20050101_0625	5.099	92.304	11	6.6
20050104_1914	10.556	91.727	10	5.7
20050106_0056	5.323	94.835	49	5.7
20050116_2017	10.934	140.842	24	6.6
20050124_0416	7.33	92.482	30	6.3
20050127_0656	7.944	94.059	38	5.7
20050127_2009	5.511	94.306	30	5.5
20050313_2212	5.486	94.595	52	5.5
20050325_0104	5.489	94.374	39	5.9

2. Data

A total of 35 events along the length of the Indonesian archipelago, Papua New Guinea, Mariana arc, and the Philippines recorded by 86 temporary broadband stations in the southeastern Caribbean were used to investigate lateral heterogeneities at the top of the inner core and constrain the physical nature of the boundaries between the eastern and the western quasi-hemispheres (Table 1 and Figs. 1 and 2). Eleven of the events from the Philippines, Papua New Guinea, and the Mariana arc had ray paths that traveled east to the southeastern Caribbean through the core beneath the eastern Pacific and arctic region and the remaining 24 had paths that traveled westward through the core beneath southern Europe and Africa. This dataset contains ray paths that sample the inner core down to 286 km beneath the outer core-inner core boundary providing an excellent dataset to explore this region of the deep Earth. We analyzed events in 2004–2005 with magnitude (M_w)